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Tropical Forest Systems: A Hydrological Approach

von

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1. Introduction

1.1

The extent and magnitude of the connections between 'Wald and Wasser', where we take Wasser to mean river, operate through the flow of water and nutrients in the tropical hillside and across the floodplain. In the hillside the water moves through the soil acting both to exchange minerals with the soil surface and to transport the minerals once in the soil solution. On the floodplain this action continues as the water flows laterally across low gradients, sometimes very slowly and over great areas. Seasonally and at times of very high runoff large areas of the floodplain are occupied by moving river water. This might be expected to provide a flushing action in which organic detritus as well as soil nutrients are removed.

1.2

In the tropical environment of Amazonas it has been widely recognised that whilst the forest is species rich and has a very high biomass, the forest draining waters may be extremely poor in nutrients, except in areas draining Mesozoic sedimentary deposits and areas of high relief (SIOLI 1975). This is largely attributed to the closed nature of the nutrient cycle in which the products of litter fall and washing of the canopy are taken up in a dense root mat close to the surface (see inter alia. SIOLI 1966, STARK 1971). The case has also been made for the direct transfer of nutrients from decomposing matter to the living plants (WENT and STARK 1968). It is generally assumed that the conventional uptake of nutrients released by weathering is small because the soils are impoverished.

1.3

The contribution to the overall nutrient balance which is made by deeper soils on the hillside depends upon the availability of material for weathering and the 'opportunity

time' or 'residence time' of the water in the soil as well as the rate and direction of movement of the nutrients in solution. These components are not however unrelated.

It is possible to suggest three broad sets of conditions which may exist within the deeper soils on the hillside.

i) If there are no soil nutrients of importance, then there can be supply neither to the plants nor the river.

ii) If the residence time is too short relative to the equilibriation time of the minerals, then weathering and exchange may not occur.

iii) If the residence time is too long (because the rate of movement is small), the material 'turnover' will be small.

It seems that with respect to the tropical rainforest each, any or all three of these conditions may occur. In particular the residence times and related rate of movement of water in the soil are seasonally and spatially variable.

1.4

The frequency of flushing of the floodplain by flood waters in the large rivers of the area such as the Negro or Solimões is largely related to seasonal variations in the river stage, events which can be modelled relatively easily and forecast with a reasonable degree of reliability. In smaller channels these flushings are related to flood events, though these themselves may be expected to show seasonal variations in frequency. The nature of the flushing is also related to the topography of the floodplain.

1.5

We have attempted to link together the hydrological effects in order to augment the closed nutrient cycling hypothesis suggested for the upper-most horizons. Our model (NORTCLIFF and THORNES 1977) is a simple analogy with a cup which is already partially full of water (Figure 1a). If more water is added the excess water overflows carrying with it very low concentration solutions. During a prolonged period of no water inputs concentration increases, so that with a further addition of water the solute concentration of overflowing water is higher.

In the soil the pore system is considered to be analagous to the cup. The coarse pore system, including non-capillary macropores, are filled and drained rapidly relative to the finer pores, so that residence time is very short, perhaps of the order of a few hours. In the soil profile (Figure 1b) it is thought that the upper part of the system fills and drains more frequently relative to the deeper part, so that residence times are shorter at the top of the profile than lower down. This is assumed to result from both a decrease in permeability and a loss of head as the permanently saturated zone is approached. In the permanently saturated zone with little movement and long residence times, concentration should be high.

Finally in the whole hillside-river plain complex (Fig. 1c) we anticipate that the floodplain will have much shorter residence times, and produce water with lower solute concentrations than the hillsides.

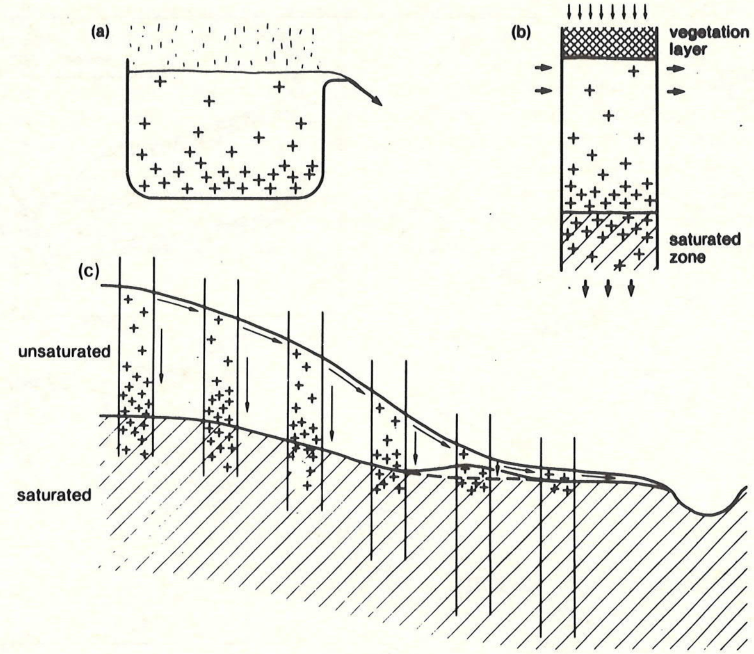

Fig. 1:

A simple cup analogy for water and solute movement in a seasonally saturated hillside

2. Experimental Design and Methods

2.1

We have designed a small experiment to attempt to elucidate some of these problems, attempting to evaluate the direction and magnitude of water fluxes in a small hillside complex, with a view to throwing more light upon the utility or otherwise of the cup analogy and the implications of these fluxes for the mineral budget. The experimental design comprises a hillslope-floodplain-river segment in the catchment of the Barro Branco at Reserva Ducke near Manaus, Amazonas. The experimental site was located in Carrasco Forest (BRINKMAN and SANTOS 1973), with canopy heights from 22 - 32 m. This forest type is typically heterogenous, with an understorey of numerous seedlings and saplings and has some herbaceous plants and palms. On the slope segment the soils are yellow and yellow/brown latosolic soils with some sand throughout the profile, with gleyed sands at the foot of the slope and flood plain area. The observations in this paper are of the period on and following 6th May 1977.

2.2

We have developed the water fluxes from observations of soil tension and moisture at a set of sites and depths on a 40 m long slope with an average inclination of approximately 20 ° and which terminates in a small flood plain (Figure 2). The tensions have been measured using standard tensiometers of the WEBSTER (1966) design and soil moisture determined gravimetrically. In addition we have measured piezometric levels on the floodplain in an attempt to relate the hillslope water flux to the activities of the stream (particularly its stage).

2.3

The basis of the computation of water fluxes is Darcy's Law which relates velocity to hydraulic conductivity and hydraulic head. The saturated conductivities were determined in the laboratory on

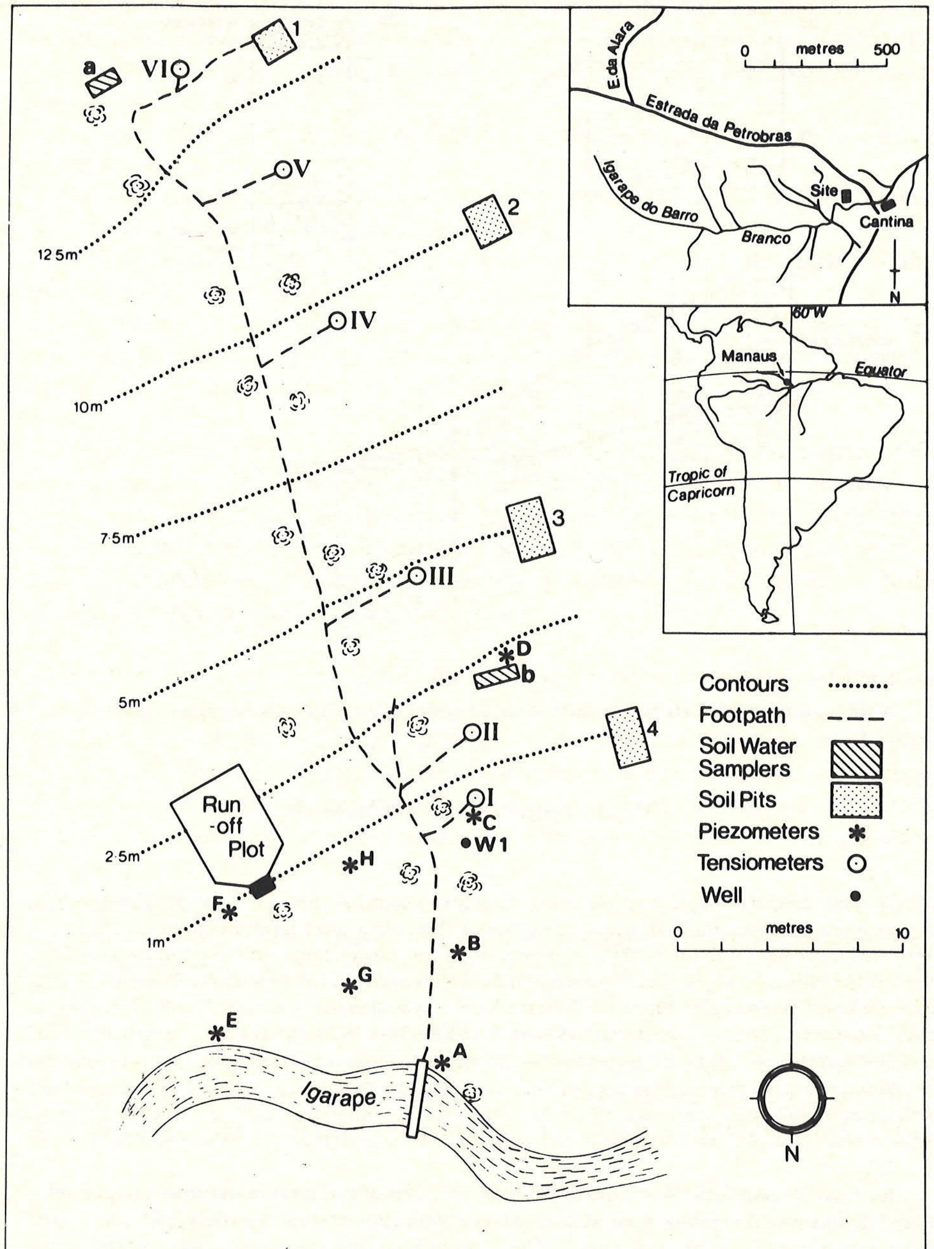

Fig. 2:
Map showing the installation of equipment at Reserva Ducke

undisturbed soil samples which gave reasonable replications and compared well with estimations from wetting front movements and infiltration tests. The latter tend to be on the high side, except on the floodplain where truly saturated conditions exist. For the purpose of our calculations we have used the conservative figure of 0.44 mm/sec. Unsaturated conductivities are a function of soil moisture and to obtain the curve relating unsaturated conductivities to potential, we have used a method derived by CAMPBELL (1974). This relies on the moisture retention function, which is the water retention (soil moisture) at various values of tension. This is determined experimentally. Figure 3(a) shows the moisture retention curve for two samples and figure 3(b) shows the unsaturated conductivity-moisture curves derived from them. The vertical and downslope components of flux were determined from the relative potential between vertically adjacent levels and at the same levels at different sites.

From these, resultant fluxes were determined using the formula

$$q_r = [\,(q_v \sin \alpha + q_d)^2 + (q_v \cos \alpha)^2\,]^{0.5}$$

where α is the slope angle

q_v is the vertical velocity

and q_d is the downslope velocity

The resultant flux angles were derived from

$$\Theta = \sin^{-1} \left(q_d \frac{\cos \alpha}{q_r}\right)$$

The flux angle represents the resultant between the downslope and vertical fluxes.

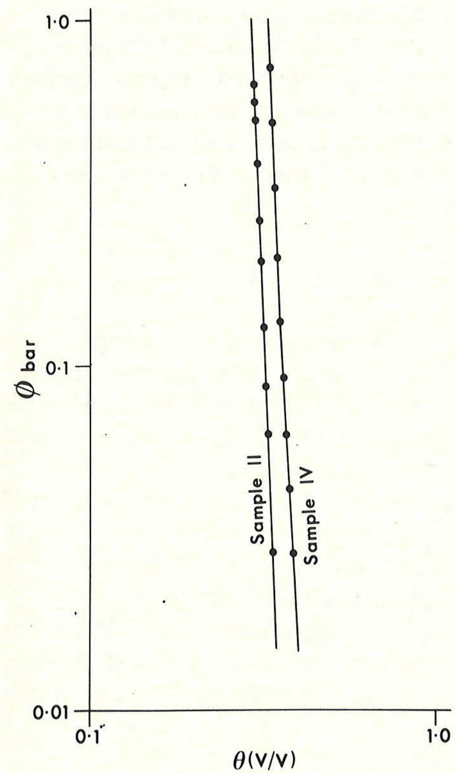

Fig. 3(a):
Moisture retention curve of moisture plotted against tension for drainage conditions for two undisturbed laboratory samples

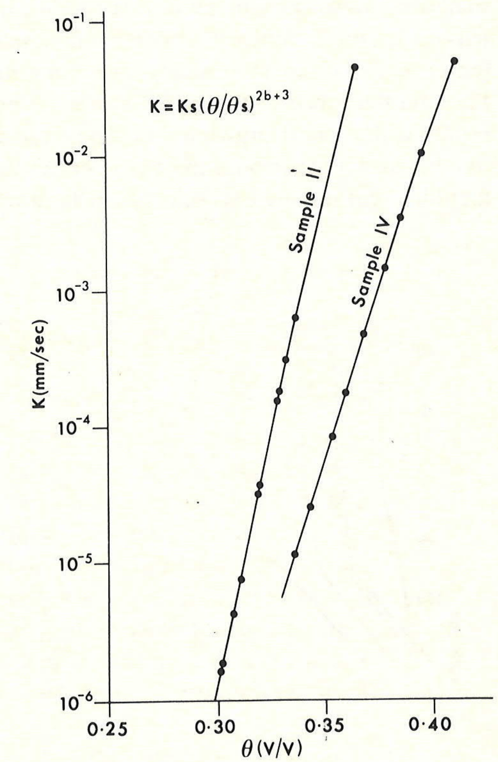

Fig. 3(b):
Derived curves for unsaturated conductivity as a function of soil moisture content

2.4

In estimating draw down characteristics of the piezometers and the discharge, we have undertaken regression of the logarithms of stage height and piezometer level height against the logarithm of time.

3. Results

3.1

The pattern of tension variation with depth and through time is indicated by a comparison of tension data for site 2 and site 6, near the bottom and top of the slope respectively (Figure 4). In the first of these, site 2, a nearly uniform distribution of tension with depth in the early part of the period illustrates the near-saturated conditions of the soil. At the base of site 2, on the 6th, 9th and 13th May, the soil is actually saturated, the pressures being positive waterhead. Under these conditions total potential for water movement is a direct and simple function of height above the datum. With some drainage there is a progressive increase in tension, especially if, as happens at site 6, there is an upward capillary loss due to evaporations.

Each profile shows individually the effects of soil structure on the development of the tension and moisture profile as well as the water flux. Thus, in the profile at site 6 drainage may be impeded due to a lateritic horizon at 80 - 90 cm and hence tensions are somewhat lower. Eventually if drainage continued within the profile, a situation in which tension is a linear function of depth will develop (i.e. $\emptyset = bZ$), so that head effects are no longer important in determining water movement. According to WEYMAN (1973), provided the situation proceeds far enough there will be an actual inversion of total potential in the profile with absolute upward flux. These conditions are likely to occur only in the dry season, because in Amazonas there is a continual replenishment of water in the wet season so that high tensions are only exceptionally developed.

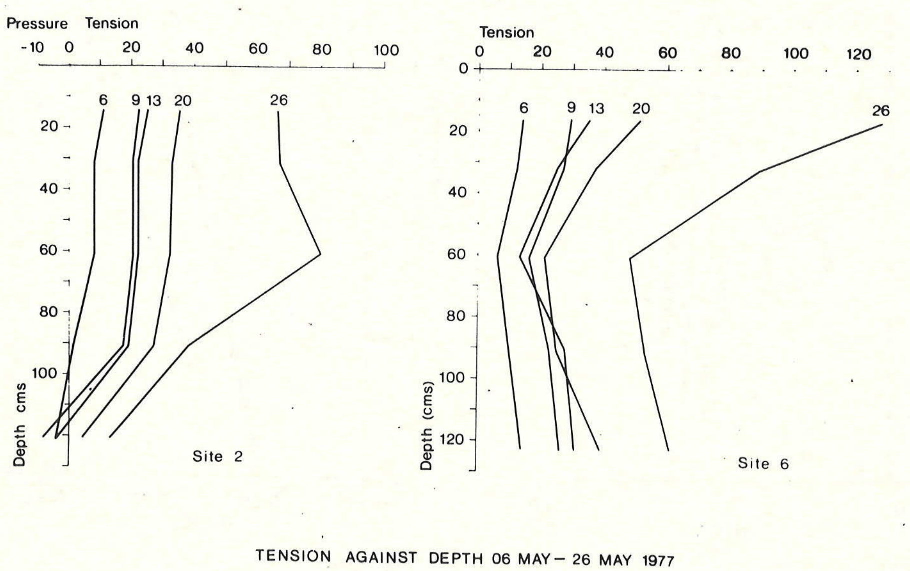

Fig. 4:
Changes in soil tension with depth and time at two sites

3.2

Figure 5 presents the distribution of 30 cm tensions over the whole length of the slope during the period of observation. Tension is plotted against height above datum. It is apparent that tension is only poorly related to head and that, therefore, the slope is almost saturated with respect to water. Actual saturation (positive pressures) are observed to occur at the foot of the slope under all conditions and within the slope during the earliest set of observations. At the foot of the slope the water actually lies on top of the ground surface on the 6th May.

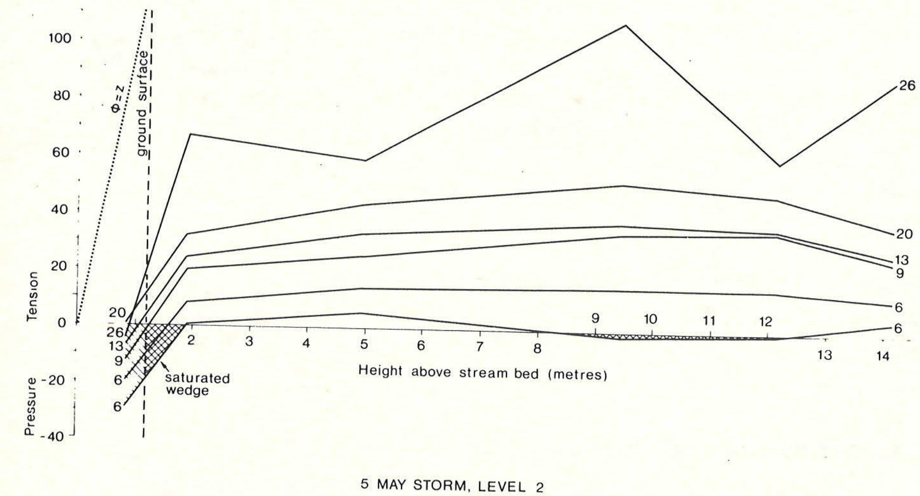

Fig. 5:
The distribution of tension over the hillslope and through time at a depth of 30 cm after the storm of May 5 - 6th

3.3

Figure 6 gives resultant fluxes at 6th May, Tables I and II give resultant flux velocities and angles for 6th and 26th May. A feature of both situations is the preponderance of near vertical fluxes, indicating little lateral movement. Occasionally as in profile 6 at the later date, some tendency of flow parallel to the slope surface was evident, but the effects are small. The major difference, however, between the two periods is the much smaller magnitude of the resultant flux during the second period. A very high flux at site 3 level 1 is believed to be due to exceptional circumstances. The average flux in the first period is 14 cms/hr (3.4 m/day) and in the second period 1.4 cms/hr (0.34 m/day).

These results are of importance to the overall consideration of water and nutrient movement, because they suggest that in the wet season, throughflow is virtually non-existent. This leads to the conclusion that water supplied to the river must be derived almost entirely from groundwater, and that any fluctuations in groundwater levels arise from vertical fluxes.

We take this to mean that in modelling concentration fluxes we can properly treat the system as a series of vertical boxes. Also it might imply that higher nutrient concentrations are to be found with depth as the rate of water removal slows down near the water

table. The earlier suggestion through the cup analogy, that there is a greater turnover at the top of the profile due to the frequent development of lateral movement is not supported by these results.

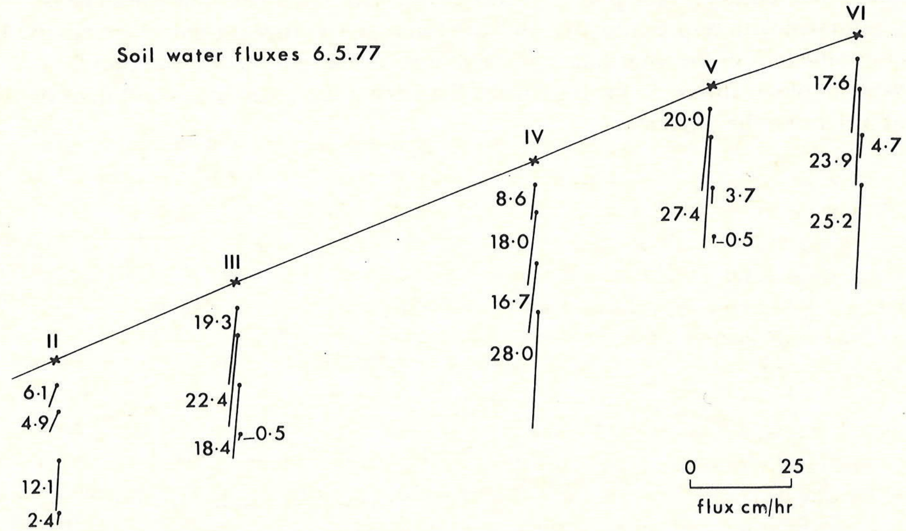

Fig. 6:
Resultant fluxes on the 6th May

Table I: Resultant Fluxes 6th May, 1977

a) Resultant Flux Velocities (cm/hr)

Level \ Profile	II	III	IV	V	VI
1	6.12	19.33	8.56	19.96	17.56
2	4.98	22.44	17.98	27.42	23.85
3	12.19	18.42	16.72	3.68	4.69
4	2.39	0.46	28.03	0.52	25.24

b) Resultant Flux Angles (^{o})

Level \ Profile	II	III	IV	V	VI
1	17.95	7.27	7.16	6.50	5.47
2	18.85	6.30	6.62	4.76	3.90
3	4.02	5.32	7.04	4.53	6.25
4	6.80	20.78	3.97	6.28	3.17

Table II: Resultant Fluxes 26th May, 1977

a) Resultant Flux Velocities (cm/hr)

Level \ Profile	II	III	IV	V	VI
1	11.19	87.13	0.64	0.02	0.14
2	5.65	0.14	0.15	0.01	0.11
3	1.41	0.02	0.06	0.05	0.12
4	8.22	0.13	0.15	0.08	0.13

b) Resultant Flux Angles (^{o})

Level \ Profile	II	III	IV	V	VI
1	12.44	1.40	2.37	7.93	3.20
2	6.88	5.63	5.08	23.83	4.85
3	0.12	21.52	11.06	11.02	6.06
4	1.36	18.61	8.17	9.54	6.28

3.4

The results from the data for Piezometer C indicate that there is an exponential draw down in the earlier stage of the storm which more or less parallels the decline in the river hydrograph (Figure 7). This suggests that the two are linked. Several authors (see inter alia

HEWLETT and HIBBERT 1963, HARR 1977, ANDERSON and BURT 1977) suggest that the slope discharge falls into two parts. In the earlier, drainage is rapid, whilst in the second it is very slow. The first part is thought to represent drainage of saturated soil, the latter unsaturated. The results presented here suggest the ıeverse pattern, being slower at first, then faster later. This behaviour suggests that at first the saturated wedge is being drained in relation to the falling river discharge, which occurs rapidly. As the river level is lowered the available head for slope drainage is increased and hence drainage is more rapid. All the evidence from piezometers indicates a very rapid response and a decline related to river discharge suggesting that drainage of the saturated wedge as a partial contributing area is responsible for the river hydrograph, and that drainage of the hillslope at this stage plays a relatively minor role.

The decay of the hydrograph itself can be fitted with two separate lines, but it seems more realistic to fit a single line after the manner of ANDERSON and BURT (1977 op. cit.).

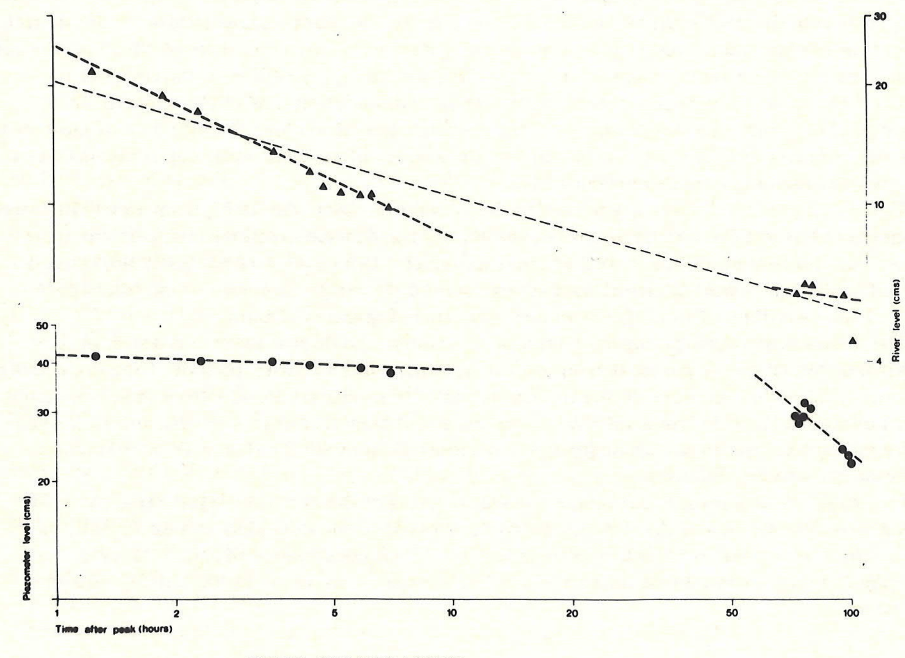

Fig. 7:
The height of water in a piezometer at the foot of the slope (piezometer C) and in the stream after the peak of the storm of 5 - 6 May

4. Conclusions

The combined evidence of saturated wedge drainage supports the view that in the wet season, at least, most of the flow is generated by rapid rise beneath the floodplain and the slope immediately adjacent to the floodplain as a direct result of rainfall infiltration, and that throughflow on the hillslope is relatively unimportant. This is consistent with certain aspects of our cup analogy and goes some way to explain the very low solute concentration found in the waters of this and similar barrancos.

5. Summary

This paper briefly examines the importance of considering the rates and magnitudes of water movement in the hillslope-river system of a tropical rainforest catchment. It is proposed that consideration of water movement is a fundamental component in understanding the release and movement of nutrients in this environment. In any such analysis it is essential that the 'opportunity time' or 'residence time' together with the availability of weatherable minerals be considered. Three conditions are suggested to account for the low solute concentrations in stream waters, each, any or all three of which may occur. (1) If there are no soil nutrients of importance then there can be supply neither to the river nor the plants. (2) If the residence time is too short relative to the equilibriation time of the minerals, then weathering and exchange may not occur. (3) If the residence time is too long (because rate of movement is slow), the 'turnover' will be small. In this context the analogy of an overflowing cup is discussed as a possible explanation of low solute concentrations.

The results presented in the paper refer to the period 6th - 26th May 1977, from a small hillslope-river segment at Reserva Ducke, Amazonas. Measurements made included soil tension, piezometric levels, river stage, infiltration rates and wetting front movement. Using Darcy's Law, water fluxes are determined. Draw down characteristics of the piezometers and river stage have been estimated using regressions of the logarithms of both these variables against the logarithm of time.

The results suggest that during the period of observation the slope is almost saturated with respect to water. Actual saturation (postive pressures) are observed to occur at the foot of the slope under all conditions and within the slope during the earliest set of observations. Results from the computation of water fluxes indicate little lateral movement, the dominant flow is at or very close to vertical. Analysis of piezometer level and river stage suggests a very close link between the two, with only limited influence from the adjacent hillslope.

In conclusion it seems that during the wet season, most of the river flow is generated by rapid rise beneath the floodplain and the slope immediately adjacent to the floodplain as a direct result of rainfall infiltration and that throughflow is unimportant. This is consistent with certain aspects of the cup analogy and goes far to explain the very low solute concentration found in the water of this and similar barrancos.

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6. Resumo

Este articulo trata con los volumenes y las velocides des de las aguas motrices del subsuelo de una cuenca pequeña del terreno forestal trópico. Se declara que es un fenomeno muy importante por el conocimiento del circulación de los alimentos en este ambiente. Necesitamos que examinar la duración de tiempo que el agua quede en el suelo en conjunto con el aprovachamiento de univerales de desagregación.

Puede ser tres causas por el nivel bajo de las minerales nutrivos en el rio. (i) Faltan en los suelos. (ii) El agua corre tan despacio que los minerales no se moven al rio. (iii) El agua corre tan rápide que la equilibración no se puede tener efecto. Hemos descrito el sistema del agua-y-suelo como una taza. (Fig. 1).

Hemos hecho un experimento para validar este modelo, con medidas de las charactericas hidrologicas de una parcela experimental en la Reserva Ducke, Manaus (Fig. 2). Tambien hemos computados los flujos de aguas subsuelas durante el periodo 6-26 May, 1977, segun el metodo de Darcy con las conductividades non-mojadas y con los medidas de pression-tension (Fig. 3,4,5). Los flujos parecen en figura 6.

Judican que los movimientos laterales son pequeñitos. La relación entre el nivel piezometrico y el nivel del rió (Fig. 7) indica que la gran parte del corriente del rió viene del terreno llano a causa de la infiltracion immediata de la precipitacion. El parte llegando de las pendientes es muy poco.

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